# Dynamic and stochastic planning problems with online decision making

Cremers, M.L.A.G.

*Chapter 5*

# A Dynamic Service Mechanic Problem for a Housing Corporation*

We study a dynamic service mechanic problem in which large maintenance activities, known already before the start of the planning period, and emergency incidents, arriving during the planning period, need to be served by the same pool of mechanics. Since this pool is not large enough, some jobs have to be subcontracted. Early assignments to subcontractors are less expensive than late ones. The goal is to assign the jobs in such a way that the total expected costs are minimal. The developed model combines elements of stochastic programming and online optimization: a two-stage recourse model with a dynamic online second stage in which a discrete event simulation is applied to generate decisions. A genetic algorithm is used to solve the entire model. Computational results are presented for randomly generated data sets inspired on real-life cases.

## 5.1 Introduction

We consider a dynamic planning problem for the repairment services of a housing corporation. Large maintenance activities are typically known well-ahead, while emergency incidents are urgent and unforeseen. A pool of skilled staff of the corporation, referred to as own mechanics, is used to serve both types of jobs. Since the number of own mechanics is not sufficient to serve all jobs, some jobs have to be outsourced to subcontractors external to the corporation. Both types of jobs can be outsourced. In this service mechanic problem we focus on a decision to make

* Joint work with J.A.S. Gromicho, W.K. Klein Haneveld and M.H. van der Vlerk. Revision submitted to Journal of Scheduling.

today for the planning period of the next weeks: which maintenance activities to assign to subcontractors and which ones to own mechanics, while taking into account the emergency incidents which become known (and need to be served) during the planning period. Since subcontracting during the planning period is more expensive than before, it can be profitable to make this decision. The decision criterion of this service mechanic problem is the expected costs of serving all jobs.

The following five characteristics are typical for our problem.

- There are two kinds of jobs: large maintenance activities which are typically known well-ahead, and emergency incidents which arrive during the planning period.
- Besides own mechanics, subcontractors are available to serve jobs, mostly during busy periods.
- Arriving incidents not only need to be assigned to mechanics, but also scheduled in the current plan. That is, for each incident a start time has to be determined.
- The group of mechanics is heterogeneous to accommodate for the various skills required by the jobs.
- Routing decisions of mechanics are not included. Hence, travel times and locations of jobs are left out of consideration. This is justified by the assumption that locations are concentrated in confined areas such as apartment blocks.

To the best of our knowledge the service mechanic problem as described above has received little attention in the literature. Related problems only cover part of the problem characteristics mentioned above.

In the field technician scheduling problem of Xu and Chiu (2001) a set of jobs, at different locations, has to be assigned to a group of field technicians with different skills. All jobs are known in advance, and rejection of jobs is allowed (which can be regarded as the availability of subcontractors).

Johns (1995) and Madsen et al. (1995b) discuss the problem of scheduling repair men. Customers call, one at a time, and immediately a time window within which the repair man starts service needs to be offered to the customer. Hence, the start time is not determined exactly, but only within certain bounds. Subcontractors are not taken into account, the group of repair men is homogeneous, and travel times are included.

In the routing and carrier selection problem (Bolduc et al., 2007; Chu, 2005) a set of requests is given, as well as a heterogeneous internal vehicle fleet. Two decisions are made: to assign each request either to an external carrier or to an own vehicle, and to route the internal fleet. A scheduling decision is not made.

In the grocery delivery problem described by Campbell and Savelsbergh (2005), rejection of requests is allowed, although this is not a decision to be made but depends on a certain probability. For accepted requests a commitment for delivery during a specific time window is made, not for delivery at a certain time. Routing of the homogeneous vehicle fleet is included.

Gerchak et al. (1996) describe the problem of planning elective surgery under uncertainty of emergency surgery. For every day in the planning period it needs to be determined how many and which elective surgeries to assign to operating rooms, while incoming emergency surgeries need to be assigned immediately. Subcontractors are not involved (the case that hospitals might be closed for emergency surgeries is left out of consideration) and operating rooms are all equivalent.

Finally, Gallagher et al. (2006) consider the problem of assigning reporters to news events arriving over time. After the arrival of a news event an acceptance or rejection decision has to be made which can be regarded as a decision to send reporters of the own company or subcontractors. If the event is accepted, a reporter is assigned to it. Unlike our service mechanics problem, start and end times, as well as the duration, of earlier scheduled events can be changed to optimize the quality of the schedule. This quality depends on the priority level of the events, the skills of the assigned reporter, and the duration. Setup times are included to accommodate for traveling between the locations of two consecutive events.

Although our service mechanic problem does not seem to have received any attention in the literature, it is an interesting problem to study. In the Netherlands, about one third of all homes are owned by (large) housing corporations. Moreover, most housing corporations employ mechanics for maintenance and emergency repairments. In addition, subcontractors are used, mostly for specialized jobs and busy periods, which is exactly the case in our problem.

Besides the practical relevance, the model we have developed to solve the service mechanic problem is also interesting from a theoretical perspective, as it combines ideas from stochastic programming and online optimization. As far as we know, no such combination has been made before, apart from our earlier papers on paratransit transport (Cremers et al., 2008, 2009b)[1].

[1] Chapters 4 and 3 of this thesis.

In Section 5.2 we give an extensive description of the service mechanic problem. Section 5.3 contains the two-stage recourse model in detail. In Section 5.4 we present the genetic algorithm to solve the model. A description of the numerical experiments and results can be found in Section 5.5, followed by a short summary and conclusions in Section 5.6.

## 5.2 Problem description

In the service mechanic problem there are two kinds of jobs: large maintenance activities which are known well-ahead and unforeseen emergency incidents which arise during the planning period. All jobs need to be served, which can be achieved by assigning them to own mechanics, overtime hours (of own mechanics), or subcontractors. In Section 5.5.4, we briefly consider the case when overtime is not allowed.

For maintenance activities (below referred to as activities) we decide before the start of the planning period whether or not to subcontract them, since this is cheaper than later on. Subcontracting is a permanent decision, while serving by own mechanics is tentative and can be changed during the planning period. For emergency incidents (below referred to as incidents) two decisions have to be made. First, immediately after arrival a permanent scheduling decision is made in which the start time of the service of the incident is determined. This is justified by the fact that usually the incidents are reported by phone and an appointment is immediately made to serve them. The second decision is to assign the incident to own mechanics, overtime hours or subcontractors. This is done tentatively first and may be adjusted to new circumstances later. But, just before the service of the incident has to start, a permanent decision is made. In a similar way, tentative assignments of activities in the first stage may be adjusted during the planning period, but just before their starting time a permanent assignment is determined.

Each job requires a specific type of mechanic, either a handyman or an expert. Experts are able to serve jobs requiring handymen, but the reverse does not hold. Besides regular hours of own handymen and experts, a number of overtime hours for each type of mechanic is available to serve jobs. We assume that jobs can only be served during overtime if the (remaining) duration is below a certain bound. Partly serving a job during overtime is allowed, but only if the job starts during regular hours and finishes in overtime. If overtime hours are used, we assume that the mechanics serve the (remainder of the) job at the end of the working day, with the possibility of violating the due time. Another assumption is that in other cases preemption is not allowed. Thus, once a job has started, interruption by an other job is not allowed. We accept these simplifications since we focus on a preplanning decision in which the actual planning does not need to be made. In addition to the own mechanics, subcontractors are used to outsource any type of job when too few own mechanics are available. The number of available handymen and experts is given and may vary during the planning period. For subcontractors, we assume that sufficiently many are available.

The data describing all activities is known from the outset and consists of the start and end times and the required number and type of mechanics needed. Incidents arrive at unknown moments during the planning period. Upon arrival, the due time of the incident is given, as well as the duration, and the required number and type of mechanics needed. The due time is the time before which the incident needs to be served and is always later than the arrival time plus the duration. Locations of jobs are not given since we assume travel times to be negligible.

The objective of the service mechanic problem is to serve all jobs at minimal expected costs. Since the labor costs of the regular hours of own mechanics are fixed, only the costs of overtime hours and subcontracting are considered. Both costs are proportional to the duration of the job and the required number and type of mechanics needed. Jobs requiring experts are more expensive than jobs requiring handymen. Furthermore, subcontracting today (before the start of the planning period) is less expensive than during the planning period, and overtime hours are cheaper than subcontracting.

## 5.3 Two-stage recourse model

To model the service mechanic problem we have chosen to develop a two-stage recourse model as known from stochastic programming (Birge and Louveaux, 1997; Ruszczynski and Shapiro, 2003). However, our model is non-standard since the second stage is modeled as an online optimization problem (Albers, 2003), while traditionally it consists of a (mixed-integer) linear programming problem. We have chosen to apply a discrete event simulation in which various online strategies are used to generate decisions, instead of optimizing the decisions. Indeed, during the planning period customers call to report incidents, for which the start time has to be communicated almost immediately. Therefore, online decision making is required in the second-stage problem. In our opinion, due to the small reaction time required, optimization is not an option and hence, heuristic strategies are applied. In the sequel we refer to these as scheduling strategies. Figure 5.1 contains a schematic overview of the entire recourse model. The first stage is described in more detail in Section 5.3.1, and the second stage in Section 5.3.2.

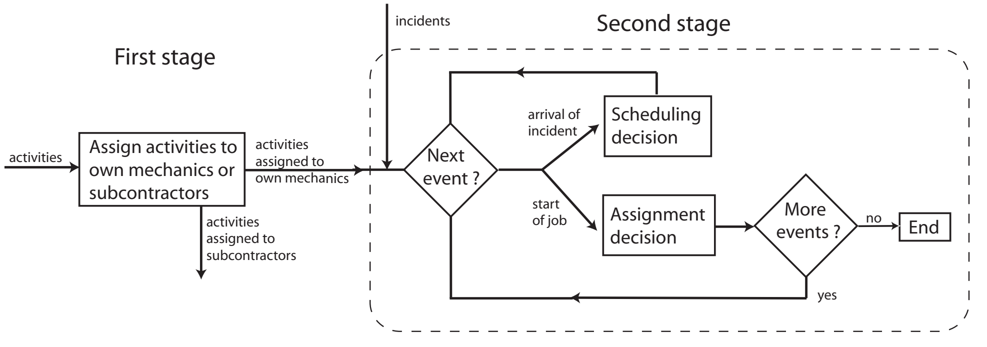


Figure 5.1. Schematic overview of the two-stage recourse model.

## 5.3.1 First stage

In the first stage, modeling the day before the planning period, the maintenance activities are assigned to mechanics: either own mechanics working regular hours or subcontractors. Overtime hours are only regarded as a recourse action. Subcontracted activities are permanently assigned, and hence they are not reconsidered in the second stage. The assignment of activities to own mechanics is tentative and can be changed during the planning period.

The following notation is used to describe the first-stage problem mathematically.

*Sets and indices*

| | |
|---|---|
| $I$ | maintenance activities, index $i$ |
| $I_e$ | expert activities, $I_e \subset I$ |
| $J$ | own mechanics, index $j$, $J = J_h \cup J_p$, $J_h \cap J_p = \emptyset$ |
| $J_h$ | handymen |
| $J_p$ | experts |
| $T$ | time periods, index $t$ |

Expert activities need to be served by experts, or subcontracted. Time is discretized in periods of equal length, which is measured in hours.

*Parameters*

| | |
|---|---|
| $b_i$ | time period in which activity $i$ starts |
| $e_i$ | time period in which activity $i$ ends, $e_i \geq b_i$ |
| $c_i$ | cost of subcontracting activity $i$ |
| $r_i$ | required number of mechanics for activity $i$ |
| $h_t$ | available number of handymen in time period $t$ |
| $p_t$ | available number of experts in time period $t$ |

Here, $c_i$ depends on the duration of the activity and the required number and type of mechanics needed.

*Decision variables (all binary)*

| | |
|---|---|
| $x_i$ | 1 if activity $i$ is subcontracted, 0 if the activity is served by own mechanics |
| $y_{ij}$ | 1 if activity $i$ is served by own mechanic $j$, 0 otherwise |
| $z_{ijt}$ | 1 if activity $i$ is served by own mechanic $j$ in time period $t$, 0 otherwise |

The mathematical formulation of the model is as follows.

$$\min \quad \sum_{i \in I} c_i x_i + Q(x) \tag{5.1}$$

$$\text{s.t.} \quad \left.\begin{aligned} \sum_{i \in I, j \in J_h} z_{ijt} &\leq h_t \qquad t \in T \\ \sum_{i \in I, j \in J_p} z_{ijt} &\leq p_t \qquad t \in T \end{aligned}\right. \tag{5.2}$$

$$\sum_{j \in J} y_{ij} = r_i(1 - x_i) \qquad i \in I \tag{5.3}$$

$$z_{ijt} = \begin{cases} y_{ij} & t \in [b_i, e_i] \\ 0 & \text{otherwise} \end{cases} \qquad i \in I,\ j \in J \tag{5.4}$$

$$y_{ij} = 0 \qquad i \in I_e,\ j \in J_h \tag{5.5}$$

$$\sum_{i \in I} z_{ijt} \leq 1 \qquad j \in J,\ t \in T \tag{5.6}$$

$$
\begin{aligned}
x_i &\in \{0,1\} && i \in I \\
y_{ij} &\in \{0,1\} && i \in I,\ j \in J \\
z_{ijt} &\in \{0,1\} && i \in I,\ j \in J,\ t \in T
\end{aligned}
\tag{5.7}
$$

The objective (5.1) is to minimize the costs of subcontracting maintenance activities plus $Q(x)$, which is the expected total costs of the second-stage problem resulting from first-stage decision $x$. In the second stage, only the costs for overtime hours of own mechanics and late assignments to subcontractors are included (see Section 5.5.1 for a numerical example). The expectation in $Q(x)$ is taken with respect to the probability distributions related to the emergency incidents. Inequalities (5.2) ascertain that in every time period the number of available handymen (experts) is sufficient to serve all assigned activities. Constraints (5.3) ensure that every activity is either served by the required number of own mechanics or subcontracted. Constraints (5.4) ascertain that if an activity is served by an own mechanic, the mechanic will serve the entire activity. Constraints (5.5) state that expert activities can not be served by handymen. Inequalities (5.6) ensure that in every time period at most one activity can be served by every mechanic. Constraints (5.7) define all variables to be binary.

### 5.3.2 Second stage

Given a first-stage assignment and observing a sequence of realizations for the emergency incidents, the second stage models the evolution of the entire planning period as a discrete event simulation in which two types of decisions are made. First, immediately after the arrival of an incident (according to a stochastic process) an online scheduling decision has to be made to determine the start time of the service of the incident. This scheduling decision is permanent. Two strategies to generate this decision will be considered: a simple one called Fix, and a more sophisticated one called Search. Notice that the scheduling strategy influences the assignment decisions, and hence the costs of the second-stage problem. Both strategies are described below.

The second decision is to assign each job to own mechanics, either working during regular hours or overtime hours, or to subcontractors. We make a distinction between tentative assignments, which are allowed to be altered later on when probably more incidents have arrived, and permanent assignments, which can not be changed anymore. Only the costs of permanent decisions are summed to the total. Hence, at the end of the simulation the total costs reflect the assignment of all jobs to mechanics. Remind that only the costs for overtime hours of own mechanics and the costs for subcontractors are considered. Below, the assignment decision is described in detail.

**Scheduling decision**

The scheduling decision determines a start time for serving an arriving incident. Since this time is communicated to the customer, it is not allowed to be changed later on during the discrete event simulation. This makes the scheduling decision very important. For example, assume that for all incidents arriving during one day the start time is set to the morning of the next day, all at the same time. Probably, only few of them can be served by own mechanics during regular hours whereas a larger number of them is expected to fit in the regular schedule if start times are spread more evenly over the planning period. In this paper, we compare two strategies to make the scheduling decision. Strategy Fix is relatively simple and strategy Search is more sophisticated.

In **Fix** the start time of each incident is set equal to the arrival time. Consequently, incidents need to be served immediately once they have become known. In practice, this might seem a little harsh, but this strategy can also be regarded as enforcing a *fixed* delay in start time.

In **Search** we attempt to (greedily) fill the gaps in the existing plan of regular hours of own mechanics by allowing a flexible delay in start time. That is, we *search* for the earliest start time such that sufficiently many own mechanics of the required type (handyman or expert) are available during regular hours to serve the entire incident. For incidents requiring a handyman, we also consider service by more expensive experts if necessary. Postponement of the start time of an incident is only considered to be feasible if the due time is not violated.

If the incident can be scheduled in the existing plan, it is tentatively assigned to own mechanics. If not, due to too few own mechanics being available to serve the incident, we decide to set the start time equal to the arrival time. Consequently, in that case the assignment decision needs to be made immediately (see below).

In Figure 5.2 we show graphically the difference between strategies Fix and Search. The length of a job denotes the duration and the height the required number of mechanics. Two activities have already been tentatively assigned using all available own mechanics in those periods, and four incidents ($i_1$, $i_2$, $i_3$, and $i_4$) arrive at different moments in time. In strategy Fix, all own mechanics are serving activity 1 at the time incidents $i_1$ and $i_2$ arrive, and hence these incidents will not be

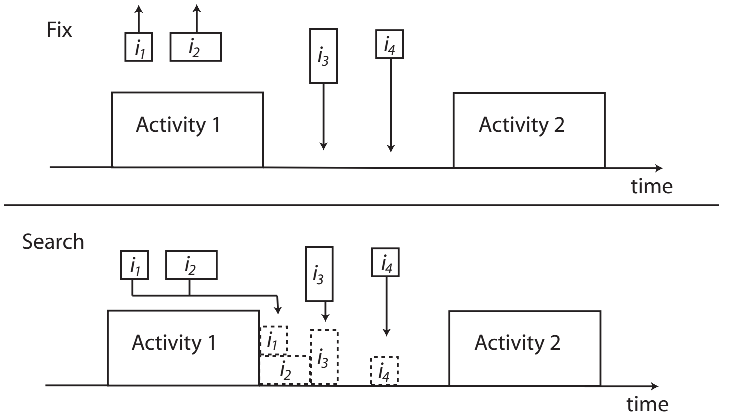


Figure 5.2. Difference between strategies Fix and Search.

served by own mechanics. For incidents $i_3$ and $i_4$ sufficiently many own mechanics are available. In strategy Search, all four incidents will be served by own mechanics since delaying the start time of incidents is allowed (at least if the due dates are not too early), and the slack time between the two activities is large enough to serve the incidents.

**Assignment decision**

In principle, the last moment to make a permanent assignment to a job is the time it has to start. When applying scheduling strategy Fix, we make permanent assignments of jobs only then. However, when applying scheduling strategy Search, we allow for permanent assignments to be made earlier than strictly necessary, at least for overtime and subcontracting decisions. This can be justified by the fact that in practice agreements with own mechanics (for overtime) and subcontractors have to be made. Hence, in our model subcontracting and serving during overtime are made permanent as soon as they come up in a tentative schedule, while an assignment to regular hours of own mechanics starts by being tentative and only becomes permanent at the moment that the job starts. Even if only part of the job is assigned to overtime, the assignment is made permanent. Again, this assumption can be motivated by practical arguments. Moreover, the assignment decision has to be made fewer times, i.e., only if the newly arrived incident can not be scheduled in the existing plan. To be able to make a better decision, we do not only consider the job that needs to be given a permanent assignment, but include all tentatively assigned jobs.

The strategy we use to make the assignment decision is based on a heuristic in the paper of Dawande et al. (2000) in which various heuristics are proposed for the multiple knapsack problem with assignment restrictions. In the heuristic on which our assignment strategy is based, items are ordered by weight (non-increasing) and one-by-one placed in the first eligible knapsack without violating capacity and assignment restrictions, as we will explain in more detail now.

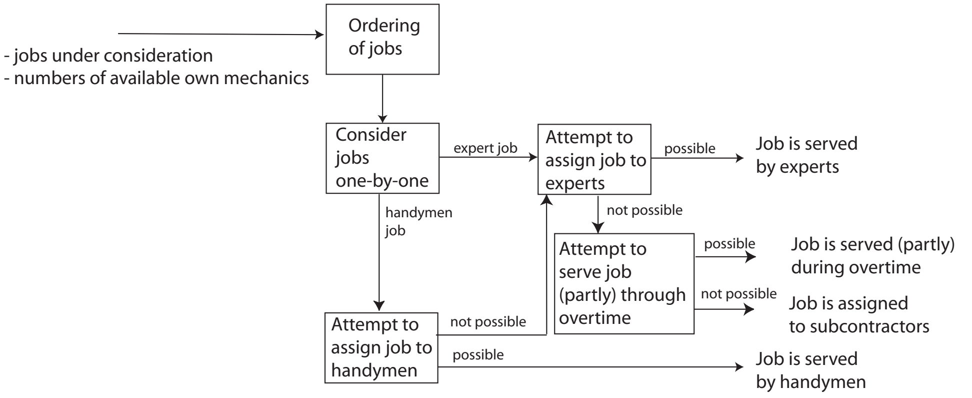


Figure 5.3. Flow chart of the assignment decision.

Figure 5.3 contains a flow chart of the assignment decision. First, the jobs are ordered on decreasing costs for subcontracting; ties are broken using increasing start time, and in remaining cases the order is arbitrary. Next, in the order specified by the list, all jobs are assigned to mechanics in the following order: handymen (only if not expert job), experts, overtime hours, or subcontractors. If overtime is not allowed (see Section 5.5.4), jobs are immediately subcontracted if assignment to experts fails. A job can be assigned to handymen (experts) if for every time period sufficiently many handymen (experts) are available to serve all jobs already assigned plus the job under consideration. A job can be (partly) assigned to overtime hours if the (remaining) duration of the job is below a certain bound, and enough overtime hours are still available. For jobs requiring handymen, we also consider service during the more expensive overtime hours of experts, if necessary. Subcontracting is always allowed.

Summarizing, the assignment of jobs to overtime hours and subcontractors is permanent, as well as the assignment of jobs which are about to start. The remaining assignments are tentative.

## 5.4 Genetic algorithm

To solve the entire recourse model, many solution techniques like e.g., local search or tabu search, exist. We have chosen to use a genetic algorithm since this method has been applied successfully to related problems (see Chu and Beasley, 1997, 1998; Cremers et al., 2008; Feltl and Raidl, 2004).

Genetic Algorithms (GAs) were developed by Holland (1975), and nowadays their principles are well known. An initial population of individuals, representing possible solutions to the given problem, is generated. Each population member has a fitness value which is determined by use of an objective function. In each iteration, parents are selected and mate to create children, which replace (part of) the population. This process is repeated until the stopping criterion is satisfied. For more details and terminology used we refer the interested reader to e.g. Goldberg (1989), Reeves (1993).

In our problem, population members (solutions) are represented by a string of binaries: for each activity a binary variable indicates whether the activity is assigned to an own mechanic (zero) or to a subcontractor (one). Consequently, there are $2^n$ possible distinct solutions, with $n$ the number of activities (first stage only). Not all solutions are feasible. A solution is said to be infeasible if in any time period more own mechanics of specific type are required than there are available. Infeasible solutions are discarded and will never enter the population.

The fitness value of population members is obtained by use of an objective or fitness function. In our problem, we want to obtain the least fit population member, i.e., the member with the lowest fitness value. Since this is counterintuitive, we will use the term cost function and expected costs instead of fitness function and fitness value, respectively.

The expected costs of a solution consist of the total costs over the entire problem horizon: the first-stage costs of assigning activities to subcontractors and the expected costs of the second-stage problem. To estimate the latter a sample of sequences of realizations for the unknown incidents is drawn. For each sequence of realizations (and given first-stage solution) the second-stage problem is solved by applying the discrete event simulation, and the costs of assigning jobs to overtime hours and subcontractors are calculated. The average costs of all sequences of realizations give the estimated costs of the second-stage problem.

To select two parents, the binary tournament selection method is used in which randomly two population members are selected of which the cheapest one is chosen as the first parent. The second parent is obtained in the same manner. Since both parents need to be distinct, the selection of the second parent is repeated as long as they are not distinct.

The one-point crossover procedure is applied to create two children. First, a crossover point is selected randomly. The first child receives the binaries to the left of the crossover point from the first parent, and the remaining binaries from the second parent. Swapping parents gives the second child. After the crossover procedure, two randomly chosen binaries are mutated in each child (solution).

Next, each solution is tested for feasibility. It is not easy to determine whether or not a solution is feasible since handyman activities can be served by handymen and experts. We have decided to perform a simple feasibility test in which solutions are regarded to be infeasible if feasibility can not be determined easily. In this test, each activity is either entirely served by handymen or by experts, but not by a combination of both. This assumption is made since it simplifies the feasibility test considerably. Three conditions are checked:

- the availability of own mechanics to serve all non-subcontracted activities,
- the availability of experts to serve all non-subcontracted expert activities, and
- the availability of handymen to serve all non-subcontracted handyman activities.

If the first or second condition is not satisfied, the solution is infeasible. If all three conditions are satisfied, the solution is feasible. In the remaining case we attempt to assign a handyman activity to experts to create a feasible assignment. If this is not successful, we regard the solution as infeasible.

Feasible solutions replace the most expensive population members, but only if their estimated costs are lower. Duplicate solutions are not allowed to enter the population, and the GA ends when a given number of feasible, non-duplicate children has been generated. The solution returned (referred to as heuristic solution) is the population member with the lowest estimated costs.

## 5.5 Numerical experiments

In this section, we describe our numerical experiments and the results. In Section 5.5.1 we describe the data generation of the instances, and in Section 5.5.2 the parameter setting of our solution method is discussed. The results of the experiments are presented in Section 5.5.3. Since in some companies overtime is not allowed, we have also computed the results for the problem without the availability of overtime hours. These results can be found in Section 5.5.4.

### 5.5.1 Data

All instances are randomly generated and contain 10 activities. The number of arriving incidents per hour follows a (discrete) Poisson process with an arrival rate of 0.625 incidents per hour. The length of the planning period is two weeks, divided into 80 periods of one hour, corresponding to 10 working days of 8 hours.

Table 5.1. Part of the data of the instances.

| | Activities | Incidents |
|---|---|---|
| start time | period 1 – 80 | - |
| due time | - | arrival time + 24 hours |
| duration | 8 – 40 hours | 1 – 8 hours (85%)<br>2 – 3 days (15%) |
| number of required mechanics | 2 – 4 | 1 – 2 |
| probability expert job | 0.15 | 0.15 |

| time period | 1 – 4 | 5 – 12 | 13 – 40 | 41 – 80 |
|---|---|---|---|---|
| available number of handymen | 8 | 8 | 10 | 10 |
| available number of experts | 1 | 2 | 2 | 2 |
| maximum overtime hours of handymen | | 40 | | 40 |
| maximum overtime hours of experts | | 8 | | 8 |

Table 5.1 contains the data of the activities and incidents. In addition, the bound on the (remaining) duration of a job to be served during overtime is 4 hours. The start time of activities and duration and number of required mechanics of jobs is uniform distributed in the given range. It might be possible that a job ends outside the planning period, in which case we set the end time equal to the last time period (without reducing the costs). Analogously, we assume that during the beginning of the planning period less own mechanics are available since they are serving jobs which started in the previous planning period. Furthermore, the costs coefficients are contained in Table 5.2. These coefficients denote the costs for one hour and one mechanic. All parameters are appropriate to describe a small to medium sized corporation.

Table 5.2. Costs per hour, per mechanic (for permanent assignment decisions).

| own mechanics | handymen | experts | subcontracting | handymen | experts |
|---|---|---|---|---|---|
| regular hours | 0 | 0 | first stage | 1 | 1.5 |
| overtime | 0.5 | 0.75 | second stage | 1.5 | 2.25 |

### 5.5.2 Parameter setting

The population size of the GA is set equal to 30 members. Based on good experiences with problems with some similar aspects (Cremers et al., 2009a, 2009b)[2], we have decided to use structured initial population members. These members are obtained by applying the assignment heuristic of Section 5.3.2 to the maintenance activities, with a reduced number of available own mechanics, or with a bound on the number of activities assigned to own mechanics, or with both. That is, a structured initial solution reserves capacity today to be able to serve incidents arriving during the planning period. For each population member, a different setting to reserve capacity is used. Since duplicate solutions are not allowed to enter the population, a solution is constructed randomly if two initial population members are the same. To generate a random solution, activities are randomly chosen and assigned to own mechanics, as long as the solution remains feasible. If all activities can be served by own mechanics, one activity is randomly chosen and assigned to a subcontractor.

The GA ends after the generation of 300 non-duplicate, feasible children. Experiments with various instances have shown that after this number the solution improves only marginally. The solution returned is the population member with the lowest estimated costs.

The sample size, to calculate the estimated costs of the second-stage problem, is set equal to 250 sequences of realizations. With this size the difference in estimated costs between the best solution and the myopic solution (see Section 5.5.3) is almost always significant on the 95%-level.

Since the genetic algorithm is a heuristic, good solutions might not always be found. Hence, to test for the randomness of the GA itself, we ran the algorithm ten times on the same instance. Since the estimated costs of the best solutions vary only by 1%, we conclude that the algorithm consistently finds solutions of similar quality.

[2] Chapters 2 and 3 of this thesis.

### 5.5.3 Results

To determine the quality of our recourse model, we compare the heuristic solution, found by the genetic algorithm, to the solution of the myopic model, which is obtained by ignoring the emergency incidents and assigning the maintenance activities to own mechanics and subcontractors at lowest possible costs. That is, the myopic solution does not reserve capacity for the unknown incidents, like the heuristic solution does. For this reason, we expect the heuristic solution to perform better than the myopic solution. To be able to fairly compare the estimated costs of both solutions, the myopic solution is also evaluated in the recourse model, using the same realizations of the incidents (common random numbers).

For a good comparison of both models (myopic and recourse model) 15 instances have been generated which are solved twice: once with the online scheduling strategy Fix and once with strategy Search. Notice that the myopic solution is always the same, only the estimated costs vary. This is caused by the influence of the scheduling strategy on the assignment decisions, and explained in detail below. In Table 5.3 we have denoted for each instance the estimated costs of the heuristic and myopic solution, for both scheduling strategies. Furthermore, the relative difference between the estimated costs of the heuristic and myopic solution is determined. For strategy Fix, CPU time is 1 – 2 minutes per instance, and for strategy Search 6 – 7 minutes per instance (with the parameter setting of Section 5.5.2, on a 2.33 Ghz Intel Core 2 Duo).

The difference in estimated costs between the heuristic solution and myopic solution is between 1% and 15% for strategy Fix, and between 1% and 21% for strategy Search. Although not reported in the table, for the average difference a 95%-confidence interval has been determined as well. For all but one problem instance the difference is significant at this level.

The myopic solution simply assigns as much activities as possible to own mechanics, ignoring the incidents and hence not reserving capacity for them. Although the relatively cheap overtime hours can be used to serve incidents, their usage is restricted to a maximum number and only allowed if the (remaining) duration is below the specified bound. Hence, since only few own mechanics are available to serve incidents, many incidents will need to be assigned to subcontractors which is 50% more expensive than before the planning period. Consequently, the estimated costs of the myopic solution are higher than those of the heuristic solution, which does take into account the incidents (by means of probabilistic information). Before the planning period the heuristic solution assigns more activities to

Table 5.3. Strategies Fix and Search, estimated costs of heuristic and myopic solution.

| | Fix | | | Search | | |
|---|---|---|---|---|---|---|
| Instance | Heuristic | Myopic | Diff. in % | Heuristic | Myopic | Diff. in % |
| 1 | 404.40 | 429.59 | 6.23 | 290.16 | 307.59 | 6.01 |
| 2 | 464.17 | 470.18 | 1.29 | 360.13 | 377.16 | 4.73 |
| 3 | 387.90 | 399.31 | 2.94 | 302.77 | 305.21 | 0.81 |
| 4 | 614.14 | 638.66 | 3.99 | 495.60 | 510.00 | 2.91 |
| 5 | 505.58 | 532.68 | 5.36 | 413.76 | 439.91 | 6.32 |
| 6 | 324.08 | 373.62 | 15.29 | 250.52 | 304.15 | 21.41 |
| 7 | 529.32 | 561.99 | 6.17 | 407.68 | 454.40 | 11.46 |
| 8 | 504.80 | 528.56 | 4.71 | 393.16 | 430.60 | 9.52 |
| 9 | 469.41 | 493.10 | 5.05 | 373.92 | 383.79 | 2.64 |
| 10 | 399.06 | 409.99 | 2.74 | 288.96 | 295.66 | 2.32 |
| 11 | 360.60 | 395.97 | 9.81 | 250.56 | 275.78 | 10.07 |
| 12 | 600.38 | 621.45 | 3.51 | 489.42 | 524.64 | 7.20 |
| 13 | 462.52 | 517.00 | 11.78 | 399.92 | 462.01 | 15.53 |
| 14 | 382.11 | 401.22 | 5.00 | 301.21 | 309.14 | 2.63 |
| 15 | 490.78 | 501.33 | 2.15 | 376.02 | 388.09 | 3.21 |

subcontractors and during the planning period less, giving higher first-stage costs but lower total estimated costs.

The scheduling strategy has a large influence on the assignment decisions and hence, on the estimated costs. In strategy Fix, the start time of incidents is set equal to the arrival time. Hence, it is not possible to fill gaps in the schedule by delaying the start of arriving incidents, as is the case in strategy Search. Consequently, in Fix during the planning period more jobs will be assigned to overtime hours or subcontractors instead of own mechanics, which is free of charge. Also before the planning period, in strategy Fix more activities (or larger ones) will be subcontracted to reserve more capacity for the emergency incidents. This results in higher estimated costs when strategy Fix is used, compared to strategy Search.

In Table 5.4 we have denoted for the heuristic solution of each instance the number of subcontracted activities (Sub), the first-stage costs and the estimated second-stage costs, for both scheduling strategies. For the myopic solution, we have only given Sub and the first-stage costs. Both effects explained above are clearly demonstrated in the table: in the myopic solution less activities are assigned to subcontractors, yielding lower first-stage costs. Moreover, for most instances the heuristic solution of strategy Search assigns less activities to subcontractors and the first-stage and estimated second-stage costs are lower, compared to strategy Fix.

Table 5.4. Strategies Fix and Search, number of subcontracted activities and costs.

| | Fix | | | Search | | | Myopic | |
|---|---|---|---|---|---|---|---|---|
| | | Costs | | | Costs | | | |
| Inst. | Sub | 1st stage | 2nd stage | Sub | 1st stage | 2nd stage | Sub | 1st stage |
| 1 | 3 | 167.50 | 236.90 | 2 | 124.50 | 165.66 | 1 | 19.50 |
| 2 | 3 | 177 | 287.17 | 3 | 234 | 126.13 | 1 | 96 |
| 3 | 3 | 117 | 270.90 | 2 | 96 | 206.77 | 1 | 51 |
| 4 | 3 | 284 | 330.14 | 4 | 323 | 172.60 | 2 | 239 |
| 5 | 5 | 171 | 334.58 | 4 | 168 | 245.76 | 3 | 95 |
| 6 | 3 | 157 | 167.08 | 3 | 157 | 93.52 | 2 | 59 |
| 7 | 3 | 287 | 242.32 | 3 | 287 | 120.68 | 3 | 187 |
| 8 | 2 | 200 | 304.80 | 1 | 128 | 265.16 | 1 | 72 |
| 9 | 4 | 207 | 262.41 | 4 | 207 | 166.92 | 3 | 148 |
| 10 | 3 | 120 | 279.06 | 4 | 174 | 114.96 | 2 | 84 |
| 11 | 3 | 110 | 250.60 | 2 | 82 | 168.56 | 1 | 28 |
| 12 | 4 | 275 | 325.38 | 3 | 250 | 239.42 | 3 | 209 |
| 13 | 3 | 237 | 225.52 | 3 | 237 | 162.92 | 3 | 193 |
| 14 | 3 | 124 | 258.11 | 3 | 124 | 177.21 | 2 | 84 |
| 15 | 3 | 108 | 382.78 | 3 | 108 | 268.02 | 3 | 102 |

On average, 13.09 handymen and 2.31 experts are required to serve the activities and incidents, while at most 10 handymen and 2 experts are available. Hence, not all jobs can be served by own mechanics, so that the use of overtime hours and subcontracting is necessary. In Table 5.5 we have denoted performance indicators for the use of overtime and subcontractors, and the ability of the scheduling strategy Search to schedule incidents in the existing plan. The standard deviation of each performance indicator is shown in parentheses. For strategy Search, on average 88% of the incidents can be scheduled in the current plan with an average delay in start time of 4 hours. This means that on average customers have to wait 4 hours for the mechanic(s) to arrive and start service, which is acceptable. For strategy Fix, all jobs are scheduled in the existing plan without delay, which is intrinsic to this strategy. Furthermore, on average every week every mechanic (both handymen and experts) has to work at most 2 overtime hours. For strategy Search, this is even less. On average, for strategy Search (Fix) 8% (14%) of the jobs are subcontracted during the planning period. To summarize, the performance indicators show that strategy Search is better able to deal with the uncertainty with respect to the incidents, as expected. The deviation of all indicators is reasonable.

Finally, we determine the effect of using the simple scheduling strategy Fix instead of the more sophisticated strategy Search, which we regard as more realistic.

Table 5.5. Performance indicators (average and standard deviation).

| | Fix | Search |
|---|---|---|
| jobs scheduled in existing plan | – | 88% (6.1%) |
| average delay in start time | 0 hours (0 hours) | 4 hours (1.6 hours) |
| average overtime per mechanic, per week | 1.4 hours (0.9 hours) | 0.5 hours (0.6 hours) |
| subcontracted jobs | 16% (5.7%) | 8% (4.8%) |

To present the results clearly, we introduce some notation. Let $x_F$ and $x_S$ be the heuristic solution of strategy Fix and Search, respectively. Furthermore, let $f^S(\cdot)$ be the estimated costs of a solution when evaluated in strategy Search. Thus, $f^S(x_F)$ is the estimated costs of the heuristic solution of strategy Fix, when evaluated in strategy Search.

To determine the effect of using strategy Fix instead of Search, we evaluate the heuristic solution of strategy Fix in strategy Search, and compare the estimated costs to those of the heuristic solution of Search. In Table 5.6 both estimated costs can be found, as well as the (average) relative difference and a 95%-confidence interval for the difference.

Table 5.6. The extra costs incurred by using simple strategy Fix instead of Search.

| Instance | $f^S(x_S)$ | $f^S(x_F)$ | Diff. in % | Conf. Int. |
|---|---|---|---|---|
| 1 | 290.16 | 297.73 | 2.61 | 3.21 – 11.94 |
| 2 | 360.13 | 363.75 | 1.01 | -1.17 – 8.40 |
| 3 | 302.77 | 311.76 | 2.97 | 3.65 – 14.32 |
| 4 | 495.60 | 496.26 | 0.13 | -3.72 – 5.05 |
| 5 | 413.76 | 417.87 | 0.99 | -0.04 – 8.25 |
| 6 | 250.52 | 250.52 | 0 | |
| 7 | 407.68 | 407.68 | 0 | |
| 8 | 393.16 | 397.10 | 1.00 | -1.29 – 9.18 |
| 9 | 373.92 | 373.92 | 0 | |
| 10 | 288.96 | 291.14 | 0.75 | -2.49 – 6.85 |
| 11 | 250.56 | 252.53 | 0.79 | -2.19 – 6.13 |
| 12 | 489.42 | 511.99 | 4.61 | 16.83 – 28.30 |
| 13 | 399.92 | 399.92 | 0 | |
| 14 | 301.21 | 301.21 | 0 | |
| 15 | 376.02 | 376.02 | 0 | |

For 6 instances the solutions of both strategies are the same, for the other 9 instances it is cheaper to use strategy Search instead of Fix. Even though only for

3 instances the difference in estimated costs is significant, we recommend to use strategy Search since it is more realistic than strategy Fix, the heuristic solution of Fix is never better than the heuristic solution of Search, and the CPU time is acceptable (6 – 7 minutes).

### 5.5.4 Results for problem without overtime

Since overtime might not always be allowed, or only to cover delays in jobs, we have also considered the problem without the possibility to assign jobs to overtime. In that case, in the assignment decision jobs can only be assigned to own handymen or experts, or to subcontractors. There are no changes in the scheduling decision.

Table 5.7 contains the results for the same 15 instances for the problem without overtime. For strategies Fix and Search the estimated costs of the heuristic and myopic solution are shown, as well as their relative difference. All results are significant at the 95%-level.

Table 5.7. Results for strategies Fix and Search for problem without overtime.

| | Fix | | | Search | | |
|---|---|---|---|---|---|---|
| Instance | Heuristic | Myopic | Diff. in % | Heuristic | Myopic | Diff. in % |
| 1 | 436.31 | 472.57 | 8.31 | 305.40 | 331.76 | 8.63 |
| 2 | 501.86 | 516.75 | 2.97 | 374.13 | 409.79 | 9.53 |
| 3 | 426.67 | 446.80 | 4.72 | 317.75 | 339.82 | 6.95 |
| 4 | 648.08 | 681.79 | 5.20 | 510.45 | 531.45 | 4.11 |
| 5 | 548.45 | 586.42 | 6.92 | 445.57 | 477.40 | 7.14 |
| 6 | 347.47 | 424.12 | 22.06 | 264.72 | 339.55 | 28.27 |
| 7 | 558.19 | 602.13 | 7.87 | 418.61 | 475.43 | 13.57 |
| 8 | 542.43 | 580.81 | 7.08 | 413.65 | 463.75 | 12.11 |
| 9 | 502.86 | 535.55 | 6.50 | 390.37 | 403.34 | 3.32 |
| 10 | 426.23 | 446.74 | 4.81 | 299.14 | 313.79 | 4.90 |
| 11 | 391.93 | 439.77 | 12.21 | 267.60 | 300.52 | 12.30 |
| 12 | 643.14 | 673.65 | 4.74 | 513.50 | 559.68 | 8.99 |
| 13 | 513.61 | 568.48 | 10.68 | 440.62 | 499.70 | 13.41 |
| 14 | 417.92 | 444.54 | 6.37 | 320.78 | 329.59 | 2.75 |
| 15 | 531.83 | 547.00 | 2.85 | 394.72 | 415.34 | 5.22 |

The solution of the recourse model is always better than the solution of the myopic model, and the relative difference is larger, compared to the problem in which overtime is allowed. This can be easily explained since overtime is less expensive than subcontracting and jobs which were served through overtime will now be assigned to subcontractors. In the myopic solution, fewer own mechanics are available to serve incidents (compared to the heuristic solution), and hence more incidents will need to be subcontracted, leading to an increase of the relative difference.

Also in the problem without overtime the estimated costs of Fix are higher than those of Search.

## 5.6 Summary and conclusion

In the Netherlands, housing corporations possess about one third of all homes and employ mechanics for maintenance and emergency repairments. In addition, subcontractors are used for specialized jobs and busy periods. In our service mechanic problem, already before the start of the planning period it is decided which maintenance activities to assign to own mechanics and which ones to subcontract, under uncertainty of the unknown emergency incidents. It can be profitable to make this decision since it is known that there are too few own mechanics to serve all jobs and subcontracting before the planning period is cheaper than during the planning period.

We have developed a non-standard two-stage recourse model to solve the service mechanic problem. In the first stage, activities are assigned to own mechanics and subcontractors. The second-stage problem is a dynamic problem in which repeatedly two decisions are made: a scheduling decision and an assignment decision. Instead of optimizing these decisions, a discrete event simulation with decision rules is applied.

Our model and solution method are flexible and can easily be adjusted, e.g., to incorporate delays in job durations, cancellation of jobs, and illness of mechanics. We have already experimented with two versions of the problem: with and without overtime.

The results are promising. The solution of the recourse model outperforms the solution of the myopic model in which the emergency incidents are ignored. The difference in estimated costs ranges from 1% to 28%, partly depending on the problem (with or without overtime) and scheduling strategy used. Strategy Search gives solutions with lower estimated costs, compared to strategy Fix, since the start time of arriving incidents is determined in a flexible manner which fills the gaps in the schedule. Since CPU times of both strategies are small, we recommend to use strategy Search. Finally, on average the waiting time for the arrival of the mechanic(s) is 4 hours, and on average mechanics have to work at most 1.4 overtime hours per week.